PRELIMINARY BACKDRAFT EXPERIMENTS

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ABSTRACT

Backdraft is defined as a rapid deflagration following the introduction of oxygen into a compartment filled with accumulated excess pyrolyzates. A scenario describing the physical and chemical fundamentals underlying backdraft phenomena is presented. A half-scale apparatus, designed to avoid dangerous over-pressures, is used to obtain data from backdraft experiments. A gas burner supplied a 150 kW natural gas fire in a 1.2 m high, 1.2 m wide, 2.4 m long compartment with a small, 2.5 cm high 30 cm wide, vent at floor level. Significant excess pyrolyzates accumulate in 180 sec, when a hatch covering a 0.4 m high 1.2 m wide vent, centered on a short wall, is opened. A gravity current carries a flammable mixed region to a spark located near the burner on the opposite wall. The rapid deflagration which results upon ignition of the mixed region is the backdraft.

INTRODUCTION

Fires can produce more fuel than the locally available oxygen can consume. This surplus fuel is called excess pyrolyzates[1]. If the compartment containing the fire is well-ventilated, the excess pyrolyzates fuel long flames which extend out openings in the compartment, rapidly spreading the fire[1]. If the compartment is closed, the excess pyrolyzates accumulate, ready to burn when a vent is suddenly opened, e.g., by a window breaking due to the fire-induced thermal stress[2] or by a firefighter entering the compartment[3,4]. Upon venting, a gravity current carries fresh air into the compartment. This air mixes with the excess pyrolyzates producing a flammable pre-mixed gas which can be ignited in many ways. A rapid deflagration moving through the compartment after ignition, consuming the accumulated excess pyrolyzates, is called a backdraft.

The fire service community has long recognized the hazards associated with backdrafts,[5]. The literature provides a definition of backdraft[6]: "Backdraft is the burning of heated gaseous products of combustion when oxygen is introduced into an environment that has a depleted supply of oxygen due to fire. This burning often occurs with explosive force." This definition is nearly correct. It is the products of pyrolysis and not the products of combustion which are responsible for backdrafts.

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SCENARIO

Consider a fire in a closed compartment where the only ventilation provided is by leakage. As the fire heats the compartment, leaks in the compartment bounding surfaces permit outflows that minimize any pressure differential[7]. A hot layer composed largely of combustion products descends around the fire causing some pyrolysis products to remain unburned. These products accumulate forming a deep, fuel-rich layer. We assume a small flame or glowing ember remains burning. Suddenly a new vent is opened. The hot, vitiated atmosphere within the compartment flows out of the upper portion of the vent. Simultaneously, cold, fresh air flows into the lower portion of the vent. The propagation of the leading edge of this cold, density driven, flow is called a gravity current[8]. A mixed layer forms due to the instabilities at the shear interface between the outflow and the inflow, and moves as a gravity current across the compartment. This mixed region is within the flammable range and is ignited when it reaches a flame or glowing ember. After ignition, a new flame propagates back along the gravity current's path as a backdraft.

APPARATUS

To test the hypothesized physical explanation of backdraft an experimental program was undertaken. The primary goal of this program was to safely simulate backdrafts in the laboratory.

Because of the explosive nature of backdraft, the experiments were limited to approximately half scale. Figure 1 shows a schematic of the apparatus giving the internal dimensions of the compartment. Figure 2 is a photo of the apparatus. In order to control the over pressure hazard, one long wall was designed as a pressure relief panel. The entire wall was hinged along the bottom and closed with a single nylon fastener at the top. Failure of the fastener relieves any over pressure greater than 1 kPa. The pressure relief panel weight is limited to <15 kg/m^2 to reduce inertia and opening time[9]. The pressure relief wall weighed approximately 13 kg/m^2. It was constructed of 18 gauge steel studs, 5.0 cm wide, 1.6 m long, 0.61 m on center. The sheathing over the studs was 18 gauge galvanized sheet steel. The panel interior was covered with a 2.5 cm thick layer of refractory fiber blanket. Tests with a large, pressurized plastic bag showed that this blow-out panel released at 0.9 ± 0.1 kPa.

A 0.9 m high and 1.5 m wide observation window was installed in the wall opposite the pressure relief panels, as shown in Fig. 2. The window glass was Neoceram, a ceramic with a negative coefficient of expansion so that it is capable of resisting temperatures over 1000K. The glass was mounted in a standard steel frame protected from the hot compartment gases by refractory insulation blanket.

To simulate a window or door, a 0.4 m high, 1.2 m wide opening was centered in the short wall opposite the burner, see work on poorly ventilated pool fires within a compartment. Figure 4b, taken - 2.5 sec after the vent is opened, just after the gravity current reaches the spark, shows the propagation of a nearly laminar flame along the mixed layer at the interface between the hot, fuel-rich, upper layer gases and the cold, oxygen-rich, fresh air entering the compartment through the lower portion of the open vent. Similar laminar premixed flames have been reported[11] on a buoyant methane layer interface within a model mine gallery, open at the bottom to allow free expansion of combustion products. Phillips[12] identified three flames: a premixed U-shaped flame burning where flammable methane concentrations occurred, a diffusion flame at the methane/air interface behind the premixed flame, and an unstable flame formed in the hot product layer sandwiched between the cold methane and air layers. In the backdraft experiments described in this paper, the burning occurs within a closed chamber which restrains the hot products. As the burnt gases expand, they force the unburned fuel and air ahead of the advancing flame front out the vent. This behavior is demonstrated by the large fire ball which burns outside the compartment, shown in Fig. 4c. The spike in the temperature, seen in Fig. 3 after 180 sec, is the flame front of the deflagration wave as it moves past the thermocouple tree on its way out of the compartment.

TABLE I - Travel times in seconds for six backdraft experiments.

Gravity Current (In)	Deflagration (Out)	Total Travel Time
2.1	2.0	4.1
3.2	1.9	5.1
2.4	2.6	5.0
3.0	2.2	5.2
4.3	2.2	6.5
5.2	1.2	6.4

In Table I, the ignition delay travel time and the deflagration wave travel time are shown in columns 1 and 2, respectively. In two experiments the sun's glare on the window washed out the video camera image. All the times are determined from the video tapes by counting the individual frames at 30 frames per second. This method is accurate to ± 0.2 sec. The time from the opening of the compartment to the time of ignition, shown in column one, ranges from 2.1 to 5.2 sec. The deflagration wave travel time, shown in column two, is the time from ignition to the time the leading edge of the wave leaves the compartment; it ranges from 1.2 to 2.6 sec. In one backdraft experiment, the last entry in Table I, the ignition delay travel time was significantly longer, and the laminar premixed flame was not observed. When ignition finally occurred, the flames were immediately hemispherical in shape and the laminar premixed flame was not observed. It should also be noted that deflagra-

Figs. 1 and 2. This vent was covered with a manually operated hatch which was opened after the fire had been burning for several minutes. The hatch was hinged at the bottom and held closed by a single throw latch at the top.

A gas burner, 30 cm square and 30 cm high, was used in all these experiments. A spark igniter mounted 5 cm above the burner, centered on the edge toward the compartment center, was the ignition source for both the burner and the backdraft. The burner was placed against the wall opposite the opening, as seen in Fig. 1. Every effort was made to seal all construction holes to control leakage. A vent, 2.5 cm high, 30 cm wide, was placed at the floor to allow for controlled leakage. A vertical thermocouple tree was placed in the geometric center of the compartment, as shown in Figs. 1 and 2. Seven thermocouples were located at 15 cm intervals, measured from the ceiling. An additional thermocouple was placed 5 cm from the ceiling to measure the ceiling jet temperature.

RESULTS

Only 8 of the 27 experiments conducted resulted in backdrafts. All these 8 experiments used natural gas as fuel. In propane experiments, the density of the propane relative to the other compartment gases resulted in accumulation of the propane low in the compartment. With only a minor difference in the densities of the hot propane and the cold air, the gravity current and resultant mixing were significantly reduced. The lack of mixing became evident when dark orange and yellow flames were observed burning along the compartment floor. The flame front would slowly propagate from the opening to the rear of the compartment. In the methane experiments which did not deflagrate, either the blow-out panel activated or the fuel flow times were too short. In the 8 experiments where a backdraft occurred, the experimental variables were relatively constant: a burn time of ~ 180 sec, natural gas as fuel, a single floor vent and a ~ 5 sec delay between burner shut off and the opening of the hatch.

The data collected in these experiments has been limited to the temperatures measured on the thermocouple tree and data recorded through the window using 35 mm cameras and video camcorders. Typical temperature histories at different heights within the compartment for an experiment in which a backdraft occurred are shown in Fig. 3. The burner was ignited at time zero. The temperature rose quickly to a maximum of 820 K at 25 seconds after ignition. The temperature then dropped as the burning rate was limited by the available oxygen. After 120 seconds the fire was nearly out; the temperature continued to drop as the compartment lost energy through its boundary surfaces. At ~ 130 seconds, the flames detached from the burner and began to dance across the floor, as seen in Fig. 4a. The dancing lasts ~ 30 seconds and is responsible for the temperature rise shown between 120 and 150 seconds in Fig. 3. The dancing flames occur in most but not all of the experiments. Similar behavior has been described by Sugawa et al.[10] in their tion travel time was considerably faster than for previous experiments. The third column in Table I is the sum of the two travel times, which is nearly constant at 5.4 ± 0.9 sec.

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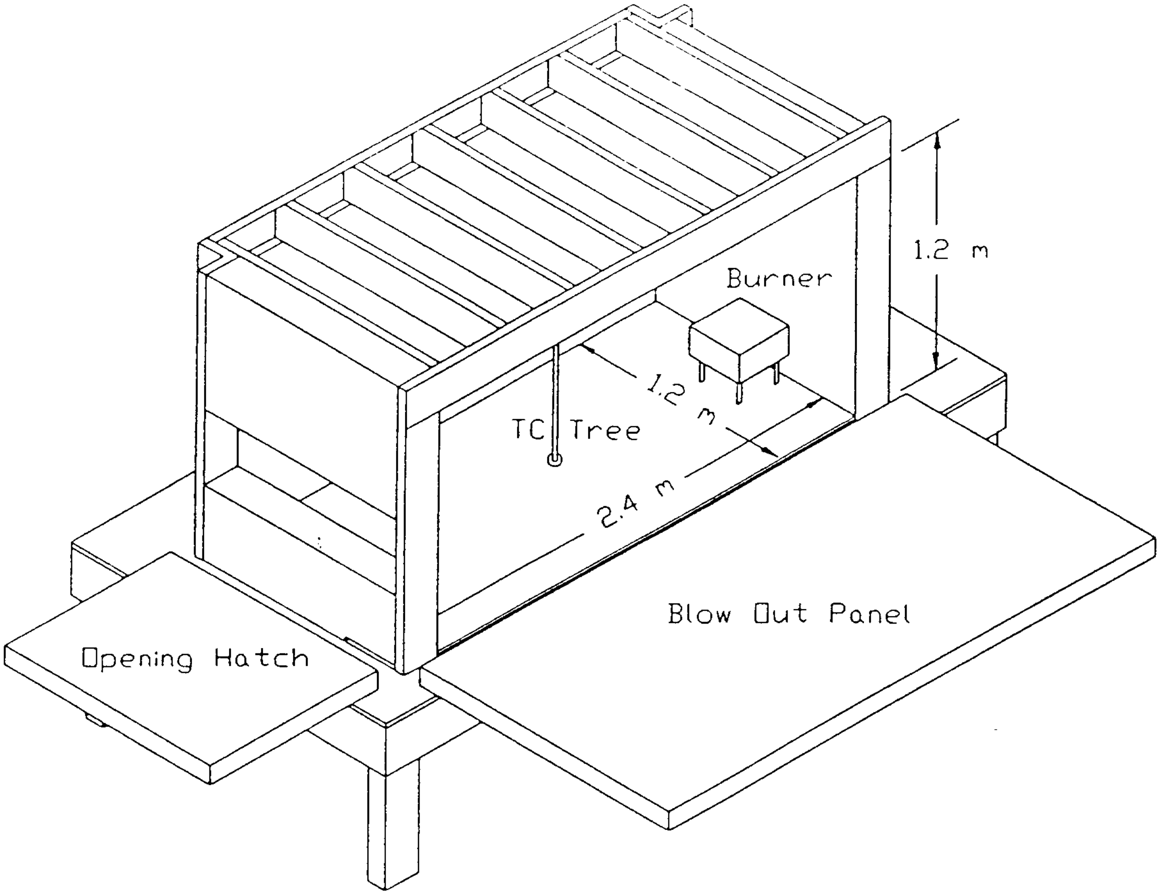

Figure 1 Schematic diagram of apparatus.

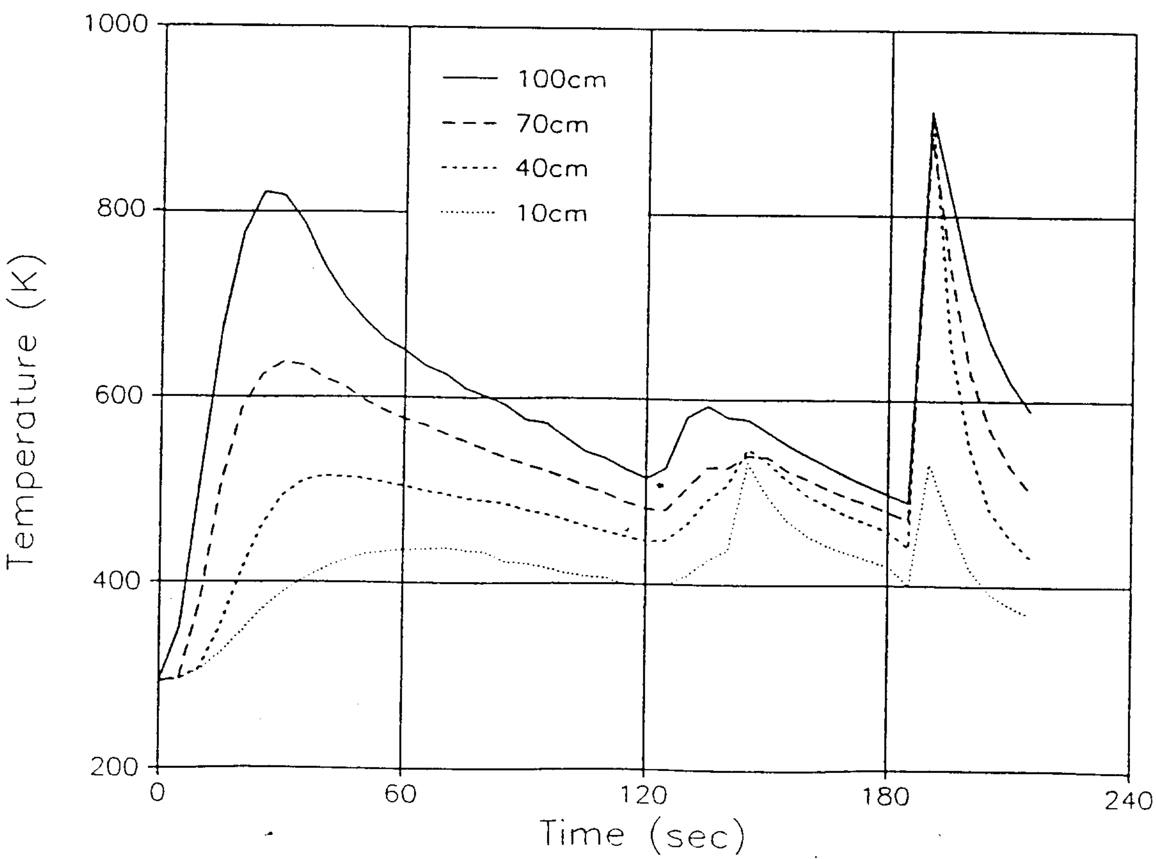

Figure 3 Representative compartment temperature histories at several heights during the third backdraft experiment listed in Table I.

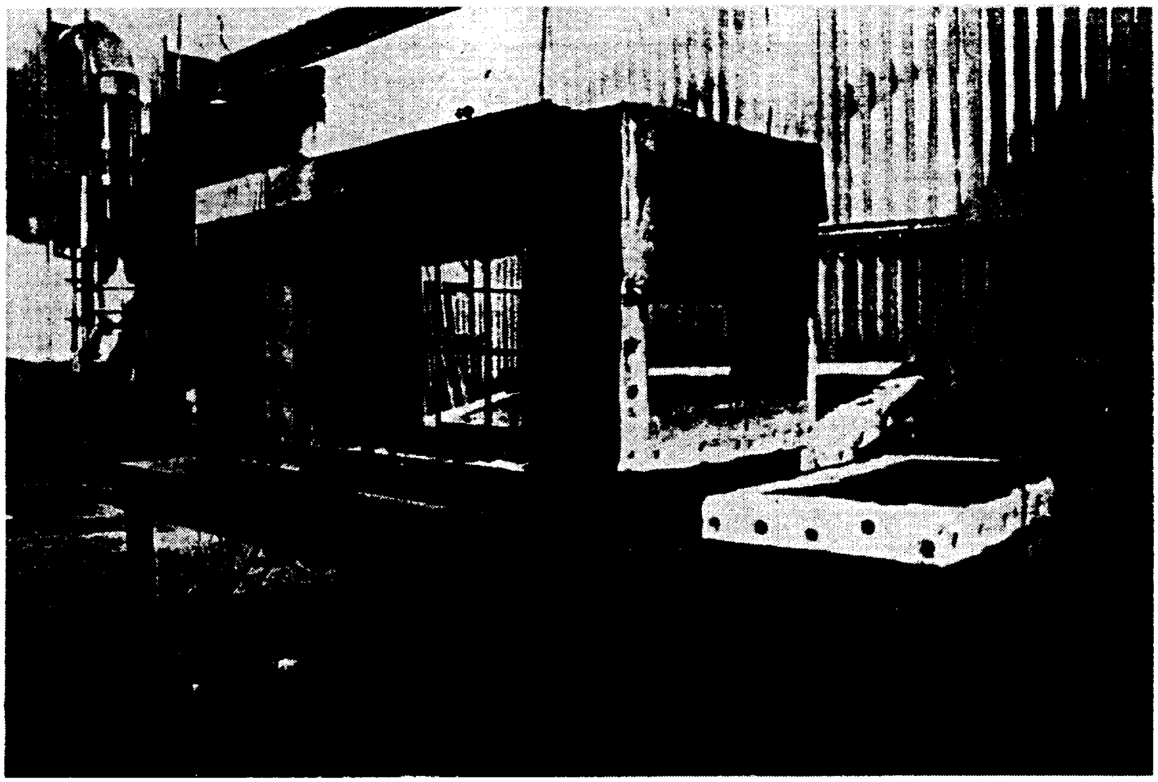

Figure 2 This photograph shows the observation window and front opening of the apparatus.

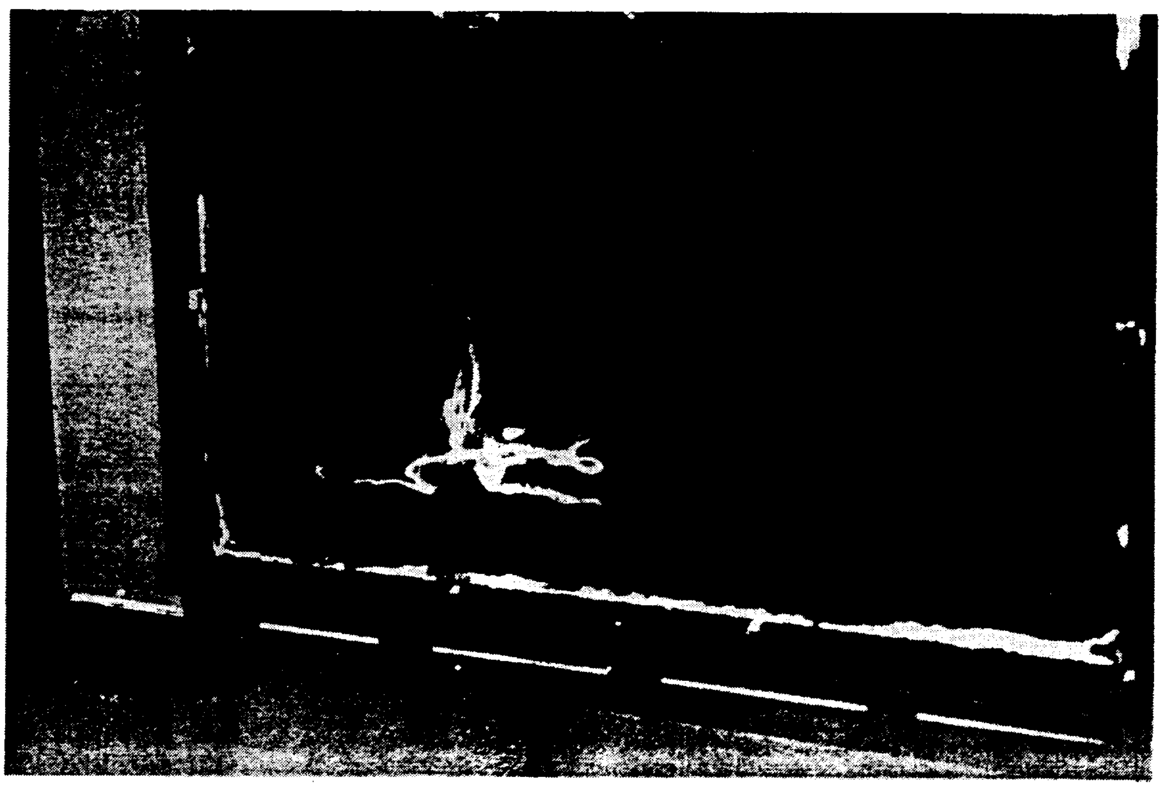

Figure 4a This photograph shows the dancing flame at -130 sec in the third backdraft experiment listed in Table I.

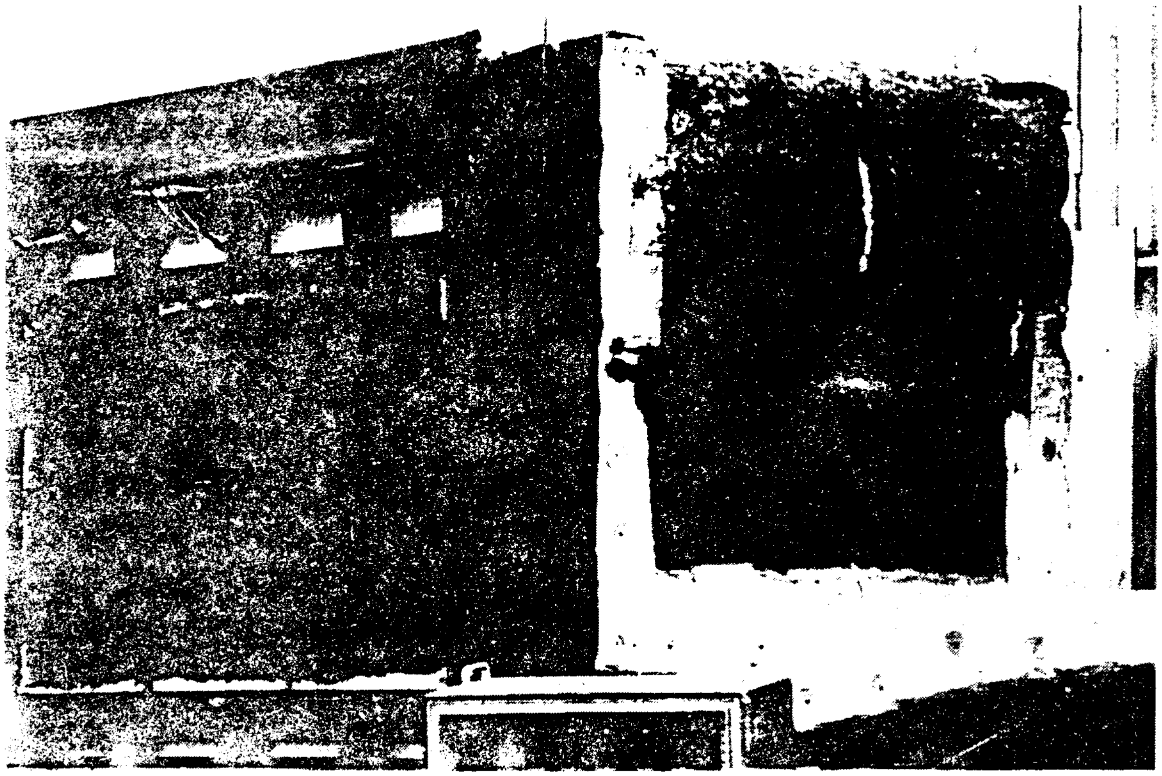

Figure 4b This photograph shows the laminar flame along the mixed layer at the interface between hot and cold layers for the fourth entry in Table I.

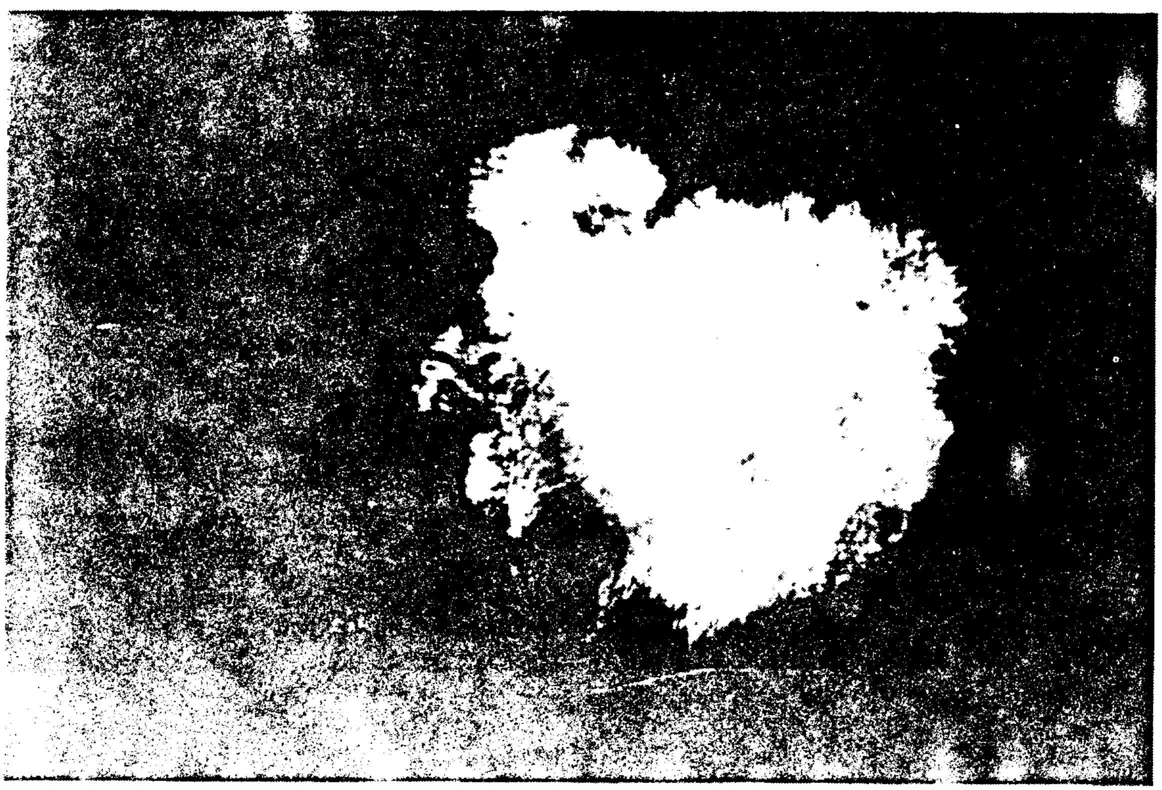

Figure 4c This photograph shows the large fire ball which bursts out of the compartment for the last entry in Table I.